AFRL-SR-BL-TR-98-

0090

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
Final 04 Feb 94 to 14 JUL 97

4. TITLE AND SUBTITLE
OPTOELECTONIC DEVICES BASED ON NOVEL SEMICONDUCTOR STRUCTURES

5. FUNDING NUMBERS
61102F
2305 DS

6. AUTHOR(S)
PROFESSOR DING

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
BOWLING GREEN STATE UNIVERISTY
106 UNIVERSITY HALL
BOWLING GREEN OH 43403-0180

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 DUNCAN AVE ROOM B115
Bolling AFB DC 20332-8050

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-94-1-0154

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVAL FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

We have proposed a class of nonlinear optical devices based on (cascaded second-order nonlinearities, in paticular, optical parametric oscillators and amplifiers, optical frequency shifters, and frequency doublers, in novel configurations. We have developed a microscopic theory for cascading optical nonlinearities and studied influence of the ionized impurities on the tunneling rates in quantum wells. We have set up a state-of-the-art nonlinear optics lab. We have systematicaloly investigated spatially-localized band-gap renormalization and band-filling effects, photoluminescence saturation due to interface traps, and tunneling of heavy holes. We have designed and grown two optimized multilayer structures for implementing optical parametric oscillators and amplifiers, and efficient frequency doublers.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18

19980129 073

DTIC QUALITY INSPECTED 3

Final Technical Report

Optoelectronic Devices Based on Novel Semiconductor Structures

(F49620-94-1-0154)

Submitted to

The U.S. Air Force Office of Scientific Research

Program Manager: Dr. Alan E. Craig

Report Period: February 4, 1994 - July 14, 1997

Principal Investigator:

Dr. Yujie J. Ding

Assistant Professor, Department of Physics and Astronomy

Principal, Center for Photochemical Sciences

Principal, Center for Materials Science

Bowling Green State University

Bowling Green, OH 43403

Project Summary

Within the funding period, we have proposed a class of nonlinear optical devices based on (cascaded) second-order nonlinearities, in particular, optical parametric oscillators and amplifiers, optical frequency shifters, and frequency doublers, in novel configurations. We have developed a microscopic theory for cascading optical nonlinearities and studied influence of the ionized impurities on the tunneling rates in quantum wells. We have set up a state-of-the-art nonlinear optics lab. We have systematically investigated spatially-localized band-gap renormalization and band-filling effects, photoluminescence saturation due to interface traps, and tunneling of heavy holes. We have designed and grown two optimized multilayer structures for implementing optical parametric oscillators and amplifiers, and efficient frequency doublers.

Results achieved within the project period

During the funding period, we have made great progress towards achieving our research objectives. The main achievements are:

- Nonlinear optical spectroscopy laboratory at Bowling Green has become fully operational.
- Spatially-localized band-gap renormalization and band-filling effect in the growth-interrupted two and three asymmetric-coupled quantum-well structures have been investigated.
- Evidence of heavy hole scattering in asymmetric coupled quantum wells has been observed.
- Impurity assisted tunneling in multiple quantum-well structures has been studied.
- Several nonlinear optical devices based on resonant and/or cascaded second-order nonlinear processes have been proposed. They include
    - Frequency doublers
    - Optical frequency shifters
    - Transversely-pumped counter-propagating and backward optical parametric oscillators and amplifiers
    - Optical power limiters
    - Optical phase conjugation
    - Waveguide couplers
    - Self-phase modulations.
- Two optimized multilayer structures have already been designed and grown for implementing frequency doublers and parametric oscillators and amplifiers.
- A general microscopic theory on cascading a wide range of nonlinear optical processes as a collective effect has been developed.
- Our publications include fifteen refereed journal papers [1-15], one workshop chapter [16], one proceeding paper [17], and twenty one conference presentations [18-38].

The detailed descriptions of our achievements for the period are as follows:

2.1. Spatially-localized band-gap renormalization and band-filling effects

In three-well structure, we interrupted the growth at every interface. As a result, one peak in photoluminescence spectrum breaks into two. They correspond to recombination of localized excitons at interface islands and of free excitons. At low temperature only the lowest peak survives, which has the linewidth of as narrow as 1 meV. We have observed pronounced broadening of the photoluminescence linewidth when the laser intensity increases. This broadening, which has not been observed before, is caused by spatially-localized band-gap renormalization.

In the modulation-doped three-well structure, the photoluminescence is dominated by impurity emission at low intensity. However, as the intensity increases, the emission peak due to the recombination of the spatially-localized excitons dominates. As the intensity increases further, the free-exciton recombination dominates. We believe we have almost completely filled the impurity sites and localized exciton states sequentially (band-filling effect).

We have made the time-resolved PL measurements in both types of our samples. After the excitation, the PL signals at the e_1hh_1 emission peak maximize at about 700 ps and 650 ps in the undoped and the modulation doped samples, respectively. This is due to the competition between the carrier intersubband relaxation and the carrier recombination. By fitting the decay curves to the exponential functions, we have obtained the PL decay time constants of 357 ps and 438 ps for the undoped and the modulation doped sample, respectively.

As shown previously at low temperatures, the radiative recombination of excitons dominates the recombination. The decay times obtained by us therefore represent the carrier life times via exciton recombination at the interface islands. We notice that the carrier life time in the modulation doped sample is ~80 ps longer than that in the undoped sample. We believe this is due to the screening of the excitons by initial electron density provided by the modulation doping. The modulation doping, therefore, significantly modifies the characteristics of carrier decay. We can translate this difference in the decay times into that of the oscillator strengths.

In the quasi-CW regime, the density of excitons can be determined as

$$N_{ex} = \tau \frac{I_{laser}\alpha}{\hbar\omega_{laser}} \tag{1}$$

where I_{laser} is the laser intensity, α is the absorption coefficient, and $\hbar\omega_{laser}$ is the energy of a single photon. The saturation intensity to completely fill the spatially-localized e_1hh_1 excitons states in the modulation doped sample is on the order of $1.2\,\mathrm{kW/cm^2}$. Assuming $\alpha \approx 10000\,\mathrm{cm^{-1}}$ at the pumping wavelength in our experiments, the exciton density is then estimated to be $2.03\times10^{16}\,\mathrm{cm^{-3}}$. The corresponding area density is $1.04\times10^{10}\,\mathrm{cm^{-2}}$. Assuming that for $I_{laser} \sim 1.2\,\mathrm{kW/cm^2}$, all the quantum states have been almost occupied, we can estimate the exciton density at the interface islands using the two dimensional density of states and the estimates of the island area ratio. The carrier density in the first electron energy level with the energy position ε_1 and the linewidth $\Delta\varepsilon$ can be determined by

$$N(e_1) = \int_{\varepsilon_1+\Delta\varepsilon/2}^{\varepsilon_1-\Delta\varepsilon/2} \rho_{2D}(\varepsilon) f(\varepsilon)\, d\varepsilon \tag{2}$$

where the two dimensional density of states, $\rho_{2D} = m^*/\pi\hbar^2$, is a constant, with m^* the effective mass and $\hbar$ the Planck's constant, $f(\varepsilon) = 1/[1+\exp(\varepsilon-\varepsilon_F)/kT]$ is the Fermi-Dirac distribution function, with ε_F the Fermi energy and k the Boltzmann constant. In the case of almost complete band filling at low temperatures, we may treat the electrons at the energy level ε_1 as

degenerate electron gas. In this case, $f(\varepsilon)=1$. Eq. (2) then reduces to

$$N(e_1)=\rho_{2D}\Delta\varepsilon(e_1) \tag{3}$$

From the PLE spectrum, we estimated that the linewidth $\Delta\varepsilon(e_1)$ is about 5 meV in our samples. Based on the area ratio, the carrier density to completely fill the e_1hh_1 exciton states at the interface islands is estimated to be $\sim 1.12\times10^{10}\,cm^{-2}$. This is in good agreement with the estimate obtained based on Eq. (1) above. This carrier density is an order of magnitude smaller than that outside the islands.

The third sample was grown by MBE on a semi-insulating GaAs substrate at the temperature of 600 C in collaboration with Naval Research Labs. The epitaxial layers consist of 20 periods, each of which is composed of two narrow asymmetric coupled GaAs quantum wells with the designed thicknesses of 50 Å and 65Å, coupled by 35Å-$Al_{0.35}Ga_{0.65}As$ barriers. The thicknesses of the barriers between the adjacent periods are 150 Å. The growth is interrupted for 60 seconds at every interface. Because of this growth interruption, interface islands with sizes larger than the average exciton radius are formed, allowing excitons being spatially-localized within these islands with separate optical transition energies from that of free-excitons. As a result, in each designed well the absorption and/or emission peaks are separated from each other corresponding to one monolayer thickness (2.8 Å) difference.

We measured the PL spectra for several pump intensities. At laser intensity of 9.7 mW/cm^2 there are two emission peaks: the one on the long wavelength side (~7780 Å) corresponds to the emission of excitons at the interface islands while the other one (~7773 Å) corresponds to the free excitons. When we change the laser intensity from 9.7 mW/cm^2 to 1.4 W/cm^2 at 4 K, the emission peak for the localized excitons loses its relative strength. Due to growth interruption, a single PL peak breaks into two because of the formation of interface islands with the size larger than the exciton radius. At low temperatures, all the carriers generated by the pump laser will be eventually relaxed down to the lowest energy levels and localized in the islands, resulting in large carrier densities. If the total area of the islands is small, it would be possible to completely fill exciton states in these islands at relatively low intensities, which manifests as the saturation of the PL peaks. This type of the band-filling effect only occurs at the spatially-localized islands. The laser intensity required to almost completely fill the localized exciton states is more than two orders of magnitude lower than that obtained on the three-well sample.

We have made the time-resolved PL measurements on our sample. At the low excitation intensity (207 W/cm^2), the PL signal at the e_1hh_1 emission peak has a decay time of about 269 ps. As the intensity increases, the decay time increases. When the laser intensity is 414, 621, and 828 W/cm^2, the decay time is about 326, 537, and 666 ps.

In the quasi-CW regime, the density of excitons can be determined by Eq. (1). The intensity required to completely fill the e_1hh_1 exciton states is about 1.4 W/cm^2. Assuming $\alpha\approx10000\,cm^{-1}$ at the pumping wavelength in our experiments, the exciton density is then estimated to be $9.75\times10^{12}\,cm^{-3}$. The corresponding area density is $1.46\times10^{7}\,cm^{-2}$. This

carrier density is more than two orders of magnitude lower than that for the three-well sample.

We grew the fourth sample: asymmetric-coupled quantum-well $GaAs/Al_{0.2}Ga_{0.8}As$ sample on a semi-insulating AlAs substrate by molecular beam epitaxy in collaboration with University of California, Los Angeles. It had twenty periods, each consisting of two QWs with designed (nominal) widths of 23 and 18 ML, coupled by a 12 ML $Al_{0.2}Ga_{0.8}As$ barrier. The adjacent periods are isolated from each other by the 53 ML thick barrier. The growth was interrupted for 10 s at each interface. In this sample, we observed relative saturation among excitonic emission peaks at different sets of interface islands. The saturation is due to sequential filling of excitonic states at different sets of interface islands. In contrast to free excitonic states, the small total area density of excitonic states at the interface islands makes their filling observable at lower excitation levels. As a result of the relative saturation, an effective blue-shift of the apparent excitonic emission peak at the islands, with a magnitude as large as ~ 6.1 meV is observed when the excitation intensity increases from $\sim 1.6\,\mathrm{W/cm^2}$ to $\sim 215\,\mathrm{W/cm^2}$. The highest intensity required to observe the effective blue-shift is about two orders of magnitude lower than that needed to observe a similar effect in a free excitonic emission peak.

Our results were published in Refs. [1,18-21].

2.2. Scattering of heavy holes

In the first asymmetric-coupled quantum-well structure, we observed the evidence of heavy-hole tunneling via acoustic phonons based on CW PL. When the sample temperature is below 80 K, the heavy holes associated with the wide well are scattered into the narrow well at high energy subands. On the other hand, when the temperature is above 100 K, the heavy holes in the narrow well are scattered into the wide well at the top of the energy band. In the second asymmetric-coupled quantum-well structure, we observed the evidence of the optically-induced redistribution of the electron-hole pairs by studying the CW photoluminescence spectra. As the laser intensity increases, the ratio of the first two heavy-hole emission intensities increases. Our preliminary analysis shows that this is the result of the scattering of heavy holes between two coupled quantum wells, strongly affected by the spatial charge separation between optically-generated electrons and heavy holes.

Our results were presented in Ref. [22].

2.3. Influence of the ionized impurities on the tunneling rates in quantum wells

We studied theoretically impurity assisted tunneling in multiple quantum well structures. We have shown that by strategically placing the impurities, it is possible to change the tunneling rates by as much as two orders of magnitude. This offers an opportunity for "engineering" structures with "customized" tunneling rates suitable for achieving intersubband population inversion and lasing. Experimental effort is under way.

The results were reported at the CLEO'96 [23] and published Ref. [2]

2.4. Surface-emitting second-harmonic generation

Following the quasi-phase matching scheme by spatially modulating second-order susceptibility [1a,2a], the surface-emitting second-harmonic generation (SHG) based on semiconductor multilayers or asymmetric coupled quantum-well domain structures has been investigated [3a], though the conversion efficiency is too low for any practical applications. To the best of our knowledge, no one has ever observed or studied the saturation of the conversion efficiency in these structures.

We have systematically investigated the SHG under relatively higher pump power. When the pump power density is equal to saturation power density, the conversion efficiency reaches 72%. The conversion efficiency is saturated if the pump power density is much larger than the saturation power density. Because of the large enhancement due to the presence of the vertical cavity, the saturation power density is greatly reduced. Therefore, the saturation of the conversion efficiency can be achieved at relatively low input power density.

For realistic dimensions based on ZnSe/ZnS or GaAs/AlGaAs materials, the saturation power density is 0.11 W/μm-4.9 W/μm for the wavelength range of the fundamental beam: 0.98-1.8 μm. If a horizontal cavity formed by two mirrors is included, the saturation power density is 0.2 mW/μm-8.7 mW/μm. The saturation occurs at much lower input power densities by using the horizontal cavity.

We can generate efficient SH radiation for a large input wavelength range or for a large output wavelength range. If the conversion efficiency decreases from 72% to 10%, $n_{2\omega} \approx 3.5$, $d \approx 1\,\mu m$, and $\lambda_0 \approx 0.9\,\mu m$, $\Delta\lambda \approx 1890\,Å$. If the input light is monochromatic, we can then generate the SH radiation within such a large output wavelength range. On the other hand, if the bandwidth of the SH radiation is narrow, we can generate efficient SH radiation for the input wavelength within the bandwidth of 3780 Å. Such a large usable bandwidth is possible only for surface-emitting geometry.

We have already designed and grown an optimized structure in collaboration with Army Research Labs. Currently, we are testing the performance of this structure as an efficient frequency doubler. Such an investigation is essential for implementing the device discussed below.

Our results were published [3,4,16,17] and presented [24-27].

2.5. Optical frequency shifters

We proposed a novel scheme for an optical frequency shifter that exploits cascaded second-order nonlinearity in a semiconductor material. The cascade comprises a sum-frequency interaction followed by a difference-frequency conversion in a coupled waveguide-to-vertical-cavity structure. For a 60-μm-long planar waveguide, efficient conversion is supported over an effective -3-dB bandwidth of 39 nm at a pump power density of

3.3 W/μm. A longitudinal in-plane cavity can reduce the required pump power density so that effective conversion occurs over a bandwidth of 20 nm at a pump power density of 6 mW/μm.

Our results were published [8] and presented [28].

2.6. Transversely-pumped counter-propagating optical parametric oscillators and amplifiers

The backward parametric oscillations in the parallel propagation configuration [4a] have not been observed due to the lack of appropriate materials for achieving quasi-phase matching. Recently, following Ref. [1a], quasi-phase matching was achieved based on GaAs/AlGaAs multilayers [3a] or asymmetric quantum-well domain structures [2a]. We have proposed to use second-order optical nonlinearities of these structures in a vertical cavity to achieve tunable and efficient transversely-pumped counter-propagating optical parametric oscillations (TPCOPOs) and amplifications (TPCOPAs). Similar to Refs. [2a,3a], the quasi-phase matching can be achieved in these structures by spatially modulating the second-order susceptibility along the growth direction. If there is no horizontal cavity, there is an optimal pump power $P_3 \approx 3.36 P_{th}$ (where P_{th} is the threshold pump power for the TPCOPOs) at which the conversion efficiency reaches the maximum value of 43.5%.

Without a mirror feedback for the signal and idler, optical parametric oscillations can occur, similar to the backward OPOs [5a], but fundamentally different from the conventional OPOs where oscillations cannot occur without the mirror feedback. If $P_3 \gg P_{th}$, there is a huge build-up of the oscillating fields inside the material. The efficient sum-frequency generation saturates TPCOPOs. The output wavelengths from the signal and idler can be tuned in a large range by changing the incident angle of the pump wave. The maximum tuning range is limited by the phase matching condition along the propagation direction of the signal or idler. Consider $GaAs/Al_{0.8}Ga_{0.2}As$ multilayers with the optimized structure dimensions: if $\lambda_3 \approx 0.9\,\mu m$, $P_{th} \approx 800\,mW$ and tuning range: 1.4–2.6 μm. Consider ZnSe/ZnS multilayers: if $\lambda_3 \approx 0.49\,\mu m$, $P_{th} \approx 100\,mW$ and the tuning range: 0.7–1.6 μm. Consider GaAs/AlAs asymmetric coupled quantum-well domain structure: if $\lambda_3 \approx 10\,\mu m$, $P_{th} \approx 100\,mW$ and the tuning range: 15–29 μm. In the presence of the horizontal cavity with the reflectivities $R_{3,4} \approx 1$, the threshold pump power (P_{th}') is reduced approximately by the factor of $1/(1-R_{3,4})^2$. The conversion efficiency reaches the maximum value of 25% when $P_3 = 4P_{th}'$. The lower maximum conversion efficiency is due to the saturation of the TPCOPO by more efficient sum-frequency generation. If $R_{3,4} \approx 99\%$, the threshold pump powers based on the three structures above are approximately 35 μW, 4.5 μW, and 4 μW, respectively.

To achieve high-power and tunable output in the mid-IR domain, we use $GaAs/Al_{0.8}Ga_{0.2}As$ multilayers. We assume $\lambda_3 \approx 2\,\mu m$ and design the structure resulting in the threshold pump power of 40 W. To achieve the maximum conversion efficiency, the pump power is $P_3 = 4P_{th}' = 160\,W$. The total output power is then 40 W. The tuning range of the output wavelengths is 3.1-5.8 μm. The proposed TPCOPOs may eventually become

the tunable and high-power compact laser sources in this domain. If the conversion efficiency decreases from its optimal value 25% to 20%, $d \approx 1\,\mu m$, and $\lambda_3 \approx 0.9\,\mu m$, we can tune the pump wavelength within the bandwidth $\Delta\lambda \approx 1300\,\text{Å}$. Our parametric processes can also be used to achieve amplifications. There is no threshold for amplifying the transmitted beam. In the case of the degenerate parametric amplification, the threshold for amplifying the reflected beam can be eliminated by coating the right end of the structure.

We grew the first multilayer structure for implementing difference-frequency generation and optical parametric amplification in collaboration with Wright Labs. The pump, input and output wavelengths are designed to be 1.06 μm, 1.58 μm, and 3.23 μm. We are in the process of implementing the parametric oscillator and amplifier based on this structure.

Our results were published [5,6,7,16] and presented [29-32].

2.7. Backward optical parametric oscillators and second-harmonic generation

We have obtained the condition for mirrorless backward optical parametric oscillation based on quasi-phase matching in a waveguide. The feedback is provided through the opposite propagation directions of the signal and idler (distributed feedback). Furthermore, we have obtained the conversion efficiency of the oscillation for the arbitrary magnitude of the pump power. By changing the incident angle of the pump beam, one can tune the output frequencies. The oscillation can be implemented based on the lasers available and using the periodically-poled KTP and $LiNbO_3$.

We have considered possibility of generating second-harmonic radiation due to interaction of two counter-propagating fundamental waves in quasi-phase-matched second-order nonlinear medium in a waveguide. The conversion efficiency reaches the maximum value at an optimum pump intensity (I_{opt}). For a large range of the pump intensities below a certain pump intensity, the efficiency is larger than that for the co-propagating configuration. The saturation intensities at which the efficiency reaches 72% for poled KTP and $LiNbO_3$ can be achieved with the lasers available. If a cavity at the second-harmonic wave is included, they can be greatly reduced. For QPM KTP, consider a domain period of $\sim 0.7\,\mu m$ for the length of the domains of 2.2 mm [5a], $\lambda_0 \approx 1.3\,\mu m$, and $\lambda \approx 2.6\,\mu m$ (fundamental frequency). One obtains the saturation intensity, $I_s \approx 1 \times 10^8\,W/cm^2$. For poled $LiNbO_3$ [6a], consider the domain period of $l_0 \sim 4\,\mu m$. If $\lambda \sim 2.2\,\mu m$, one can use the 7th-order gratings in the domains with the period of $l_0/7$ for QPM. Assuming $L \approx 2.6\,cm$, one obtains $I_s \sim 59\,MW/cm^2$. To observe SHG, one can use a pump intensity $\approx 0.01\,I_s$ for the conversion efficiency of $\eta \approx 2\%$. For the two examples considered above, the corresponding pump intensity is $1\,MW/cm^2$, and $0.59\,MW/cm^2$, respectively. At these pump intensities, $\eta \approx 4\eta'$, where η' is the conversion efficiency for the co-propagating configuration. To observe the conversion efficiency peaking, one needs to increase the pump intensity to more than I_{opt}. For the KTP and $LiNbO_3$ considered above $I_{opt} \approx 5 \times 10^8\,W/cm^2$ and $\approx 2.9 \times 10^8\,W/cm^2$, respectively. At these intensities the other effects masking SHG are negligible [6a,7a]. In the presence of a cavity for the SH waves with the mirror reflectivities of $\approx 99\%$, the saturation intensity reduces to

2 MW/cm^2 and 1.2 MW/cm^2, respectively, for the two examples considered above. The short-period domains can be used as an output coupler for an AlGaAs laser diode and as a QPM nonlinear medium (dual function) to generate blue light. The overall efficiency is larger than that for the co-propagating SHG. Our configuration can be also used for phase detectors.

Our results were published in Refs. [11-13] and presented in Refs. [33-37]. We have established collaboration with Naval Research Labs to implement backward parametric oscillation and amplification and second-harmonic generation in periodically-poled $LiNbO_3$.

2.8. Optical power limiters

In the surface-emitting second-harmonic generation (SHG), the SH radiation propagates at the direction normal to the propagation axis of the two fundamental counter-propagating beams. Due to the conversion of the power of the fundamental beams to that of the SH radiation, one should expect that the power of the fundamental beam that propagates along the negative z axis at the exit plane ($z=0$), $P_2(0)$, can be very small if the input power is much larger than the saturation power, see Section 3. On the other hand, if the input power is much lower than the saturation power, $P_2(0)$ is unaffected. Therefore, if $P_2(0)$ is taken as the output and $P_1(0)$, i.e. the input pump power, is taken as the input, $P_2(0)$ vs. $P_1(0)$ demonstrates the characteristic of a power limiter. We can introduce the threshold power density - the input power per the unit waveguide width, at which $P_2(0)$ starts to decrease as $P_1(0)$ increases. This threshold power density is essentially the same as the saturation power density introduced in Section 3. For a realistic structure based on GaAs/AlGaAs materials, the threshold pump power is ~ 10 mW/μm.

Our scheme for power limiting is more advantageous than those so far. First of all, the output power can be eliminated more effectively by increasing the input power (the exponential dependence on the input power rather than inversely proportional as in the scheme based on two-photon absorption). Secondly, since we have limited the output power by converting most of it into the SH power, we do not use absorption for limiting. Therefore, our device can take much higher input power.

Our results were published and presented [3,16,25,27].

2.9. Optical phase conjugation and waveguide coupling

Two waveguides are arranged with one on the top of the other in the common vertical cavity. The lower waveguide serves as a pump, with two relatively strong counter-propagating waves, $E_1(\omega)$ and $E_2(\omega)$, generating the second-harmonic wave $E_{2\omega}$. An input beam $E_3(\omega)$ propagating along the positive z axis in the upper waveguide interacts with $E_{2\omega}$, generating signal wave $E_4(\omega)$, that propagates along the negative z axis in the upper waveguide. $E_4(\omega)$ is the phase-conjugated wave of $E_3(\omega)$.

We first consider the symmetric waveguides, i.e. the structures of both waveguides are the same. We can plot the conversion efficiency from E_3 to E_4 or the reflectivity of the phase-conjugate mirror vs. the input pump power. When $P_p/P_0=1$, $\eta_c \approx 9.4\%$. However, if $P_p/P_0 \geq 1$, η_c vs. P_p/P_0 displays saturation. If $P_p/P_0 >> 1$, η_c approaches R_4. Therefore, the device acts as an optical phase-conjugate mirror with the reflectivity of R_4.

Now, can we expect a gain based on our scheme (i.e. $\eta_c > 1$)? In this case, we can use two waveguides that have different structures. We introduce a parameter to denote the structure difference of the two waveguides: $\xi = d_{eff,p}/d_{eff,c}$, where $d_{eff,p}$ and $d_{eff,c}$ correspond to the effective SHG thicknesses in the pump and phase-conjugate waveguides, respectively. Therefore, the conversion efficiency can be plotted vs. P_p/P_0 for different values of ξ. There is a gain if $\xi > 1$ and P_0/P_s is sufficiently large. It is interesting to note that η_c can be ∞ if $\xi > 4$. *This corresponds to waveguide coupling; i.e. two counter-propagating waves can be generated in the upper waveguide without any input in the waveguide.* One can plot the threshold pump power P_{th}/P_0 vs. ξ_{th} at the onset of the waveguide coupling. P_{th}/P_0 decreases dramatically as ξ_{th} increases for its value slightly larger than 4. However, as ξ_{th} increases further, P_{th}/P_0 decreases slowly.

Our results were published and presented [3,9,14,16,27,38].

2.10. Self-phase modulations

The proposed structure consists of the waveguide sandwiched between two mirrors with high reflectivities at frequency 2ω. Another high-reflectivity mirror is placed at one end face to reflect the fundamental waves back into the structure. We modulate the second-order susceptibility $\chi^{(2)}$ along the x (growth) direction by growing asymmetric quantum-well domains or multilayers. E_1 and E_2 (E_3 and E_4) are the incoming (reflected) TM- and TE-mode fundamental waves, respectively. Different from the configurations for an optical power limiter and phase conjugation, the input wave has both TE and TM components, which permits a unique nonlinear wave coupling among five optical fields. Note that two SH components are generated by the mixing of two counter-propagating fundamental waves (i.e. E_1E_4 and E_2E_3), and they in turn couple back with fundamental waves to provide phase modulation.

First of all, consider undepleted pump approximation. This condition applies to the case of a weak signal being modulated by an orthogonally polarized strong pump beam (i.e. TE-mode signal and TM-mode pump). The phase difference between the reflected and input signal waves can be up to π depending on the pump power. Therefore, the structure can be used as half-wave plate or quarter-wave plate. For very small value of $\Delta\beta L$, where $\Delta\beta$ is the difference of the wave vectors of the TE and TM waves and L is the waveguide length, the critical pump intensity for the phase change to occur is ~ 0.1 W/μm for a realistic structure based on GaAs/AlGaAs materials.

Secondly, we consider equal TE and TM amplitudes. This situation can be realized by orientation of the input beam at a 45° angle. In this set-up, unlike the one above, there is no

controlling (pump) beam, so that the input is now modulated by itself (i.e. self-action). Similarly, the phase difference can be up to π depending on the input beam intensity.

For small values of $\Delta\beta L$ and low input intensities the phase shift is linear with intensity, and effective values of n_2 can be estimated to be $\sim 3 \times 10^{-12}\,\mathrm{cm^2/W}$ for a realistic structure. This type of phase behavior was also found in Ref. [8a], where the nonlinear phase change was provided by the wave-vector mismatch between the fundamental and the SH waves.

Our results were published and presented [10,16,27].

2.11. Microscopic theory for cascading optical nonlinearities

A general microscopic theory treating cascading of a wide range of nonlinear optical processes as a collective effect is developed. We have shown that virtually any third-order nonlinear process can be successfully emulated by a cascaded combination of two second-order processes. These processes include self-phase modulation, temporal and spatial soliton propagation, phase conjugation and others.

Our results were submitted for publication [15].

2.12. List of the principal investigator's publications in the covered period

Journal publications

[1] A. G. Cui, Y. J. Ding, S. J. Lee, J. V. D. Veliadis, J. B. Khurgin, S. Li, D. C. Reynolds, and J. Grata, ''Spatially-localized band-gap renormalization and band-filling effects in growth-interrupted asymmetric superlattices," J. Opt. Soc. Am. B 13, 536 (1996).

[2] J. V. D. Veliadis, J. B. Khurgin, and Y. J. Ding, ''Engineering of the nonradiative transition rates in modulation doped multiple quantum wells," IEEE J. Quant. Electr. 32, 1155 (1996).

[3] J. B. Khurgin and Y. J. Ding, ''Resonant cascaded surface-emitting second-harmonic generation - a strong third-order nonlinear process," Opt. Lett. 19, 1016-1018 (1994).

[4] Y. J. Ding, S. J. Lee, and J. B. Khurgin, ''Cavity-enhanced and quasi-phase matched optical frequency doublers in surface-emitting geometry," J. Opt. Soc. Am. B. 12, 1586-1594 (1995).

[5] Y. J. Ding, S. J. Lee, and J. B. Khurgin, ''Transversely-pumped counter-propagating optical parametric oscillations and amplifications," Phys. Rev. Lett. 75, 429-432 (1995).

[6] Y. J. Ding, S. J. Lee, and J. B. Khurgin, ''Tunable and efficient transversely-pumped counter-propagating optical parametric oscillators and amplifiers: conversion efficiencies and tuning ranges," IEEE J. Quant. Electr. 31, 1648-1658 (1995).

[7] Y. J. Ding, and J. B. Khurgin, ''Mirrorless optical parametric oscillators," J. Nonl. Opt. Phys. Mat. 5, 223-246 (1996).

[8] O. Gorbounova, Y. J. Ding, J. B. Khurgin, S. J. Lee, and A. E. Craig, ''Optical frequency shifters based on cascaded second-order nonlinear processes," Opt. Lett. 21, 558-560 (1996).

[9] Y. J. Ding, J. B. Khurgin, and S. J. Lee, ''Optical phase conjugation and waveguide coupling by cascading transverse second-harmonic and difference-frequency generation in a vertical cavity," to appear in Opt. Quant. Electr. Nov.'96 issue.

[10] S. J. Lee, J. B. Khurgin, and Y. J. Ding, ''Self-phase modulation by means of cascaded resonant surface-emitting second-harmonic generation," J. Opt. Soc. Am. B 12, 275-280 (1995).

[11] Y. J. Ding and J. B. Khurgin, ''Second-harmonic generation based on quasi-phase matching: a novel configuration," Opt. Lett. 21, 1445-1447 (1996).

[12] Y. J. Ding and J. B. Khurgin, ''Backward optical parametric oscillators and amplifiers," IEEE J. Quant. Electr. 32, 1574-1582 (1996).

Pending journal publications

[13] Y. J. Ding and J. B. Khurgin, ''Quasi-phase-matched mirrorless nondegenerate backward optical parametric oscillation," submitted to Opt. Lett.

[14] S. J. Lee, J. B. Khurgin, and Y. J. Ding, ''Directional couplers via the cascaded resonant surface-emitting second-harmonic generation," submitted to Opt. Comm.

[15] J. B. Khurgin, A. Obeidat, S. J. Lee, and Y. J. Ding, "Cascaded optical nonlinearities: microscopic understanding as a collective effect," submitted to J. Opt. Soc. Am. B.

Proceeding and workshop

[16] Y. J. Ding, J. B. Khurgin, and S. J. Lee, ''Nonlinear optical devices based on second-order nonlinearities of semiconductor multilayers and asymmetric quantum-well domain structures," invited by a Nobel Laureate, Prof. T. D. Lee, July 4-13, 1994, the China Center for Advanced Science and Technology, Beijing, China; CCAST-WL Workshop Series: Vol. 38, Ultrafast Phenomena, Eds. K. Shum, Y. J. Ding, and X. C. Zhang, pp. 60-88, Gordon&Breach, Beijing, 1994.

[17] J. B. Khurgin, S. J. Lee, and Y. J. Ding, ''Efficient resonant frequency-doubling in semiconductor multilayers," NAECON'94 Proceeding, pp. 520-524.

Conference presentations [(*) - refereed; (**) - invited]

[18] * A. G. Cui, O. Gorbounova, Y. J. Ding, J. V. D. Veliadis, S. J. Lee, J. B. Khurgin, and K. L. Wang, ''Large blue shift due to band-filling at interface islands in coupled quantum wells," QELS'96 (Anaheim, CA, Jun. 2-7, 1996), Paper QME1.

[19] Y. J. Ding and J. B. Khurgin, ''Nonlinear photoluminescence decay in the presence of saturated deep traps in quantum wells," 1994 OSA Ann. Meet., Paper TuZ4.

[20] A. G. Cui, Y. J. Ding, S. J. Lee, J. V. D. Veliadis, J. B. Khurgin, S. Li, and D. S. Katzer, ''Excitonic emission linewidth broadening in asymmetric superlattices," 1994 OSA Ann. Meet., Paper TuZ5.

[21] * Y. J. Ding, A. G. Cui, S. J. Lee, J. V. D. Veliadis, J. B. Khurgin, S. Li, and D. S. Katzer, ''Observation of intensity-induced photoluminescence linewidth broadening in periodic asymmetric coupled three quantum wells," Nonlinear Optics: Materials, Fundamentals, and Applications, July 25-29, 1994, Waikoloa, Hawaii, Paper TuP20.

[22] A. G. Cui, Y. J. Ding, O. Gorbounova, J. V. D. Veliadis, S. J. Lee, J. B. Khurgin, and K. L. Wang, ''Acoustic-phonon-assisted tunneling of heavy holes between asymmetric coupled quantum wells," ILS'95, Paper MYY4.

[23] * J. V. D. Veliadis, Y. J. Ding, and J. B. Khurgin, ''Impurity scattering enhancement of the acoustic phonon limited intersubband transition rate," CLEO'96, Paper CThK33.

[24] Y. J. Ding, S. J. Lee, and J. B. Khurgin, ''Efficient frequency doublers based on surface-emitting second-harmonic generation," 1995 OSA Ann, Meet., Paper TuS4.

[25] * J. B. Khurgin, S. J. Lee, and Y. J. Ding, ''Efficient resonant surface-emitting second-harmonic generators and optical power limiters based on multilayers or asymmetric quantum wells," Nonlinear Optics: Materials, Fundamentals, and Applications, July 25-

29, 1994, Waikoloa, Hawaii; Dig. (IEEE, 1994), pp. 321-323, Paper WP5.

[26] J. B. Khurgin, S. J. Lee, and Y. J. Ding, "Efficient resonant frequency-doubling in semiconductor multilayers," NAECON'94, May 23-27, 1994, Dayton, OH.

[27] * J. B. Khurgin, S. J. Lee, and Y. J. Ding, "Resonant surface SHG as a universal nonlinear-optical module," CLEO'94, Paper CThD7.

[28] * O. Gorbounova, Y. J. Ding, J. B. Khurgin, and S. J. Lee, "Efficient optical frequency shifters based on cascaded resonant semiconductor second-order nonlinearities," CLEO'95, Paper CWF9.

[29] ** Y. J. Ding and J. B. Khurgin, "Optical parametric oscillators without any cavity in novel configurations," invited Talk, LEOS'96 Ann. Meet., Boston, MA.

[30] * Y. J. Ding, J. B. Khurgin, and S. J. Lee, "Tunable transversely-pumped counter-propagating optical parametric oscillators and amplifiers," CLEO'95, Paper CFA8.

[31] * Y. J. Ding, J. B. Khurgin, and S. J. Lee, "Tunable transversely-pumped counter-propagating optical parametric oscillators based on semiconductor structures," 1995 Quant. Optoelectr. Top. Meet, Paper QThE4.

[32] ** Y. J. Ding, J. B. Khurgin, and S. J. Lee, "A novel configuration for optical parametric oscillators and amplifiers," Novel optical materials and applications, May 28-Jun. 2, 1995, Cetraro, Italy.

[33] Y. J. Ding and J. B. Khurgin, "Backward optical parametric oscillation without any cavity based on quasi-phase matching," to be presented at the 1996 OSA Ann. Meet., Paper MYY8.

[34] * Y. J. Ding and J. B. Khurgin, "Degenerate backward optical parametric oscillators and amplifiers: conversion efficiencies and gain saturation," Nonlinear Optics: Materials, Fundamentals, and Applications, July 8-12, 1996, Maui, Hawaii.

[35] * Y. J. Ding and J. B. Khurgin, "Degenerate backward optical parametric oscillation and backward second-harmonic generation," IQEC'96, Sydney, Australia, Jul. 14-19, 1996, Paper WL47.

[36] * Y. J. Ding and J. B. Khurgin, "Efficient backward second-harmonic generation in quasi-phase-matched second-order nonlinear medium: a novel configuration," joint session of CLEO'96 and QELS'96 (Anaheim, CA, Jun. 2-7, 1996), Paper JTuB2.

[37] Y. J. Ding, S. J. Lee, and J. B. Khurgin, "Mirrorless degenerate backward parametric oscillations based on second-order nonlinearity of novel semiconductor structures," 1994 OSA Ann. Meet., Oct. 2-7, 1994, Dallas, TX, Paper FA2.

[38] Y. J. Ding, S. J. Lee, and J. B. Khurgin, "Optical phase conjugation by cascading transverse second-harmonic and difference-frequency generation in a vertical cavity," OSA Annual'95, Paper ThDDD1.

Other references

[1a] N. Bloembergen, U.S. Patent No. 3 384 433 (1968).

[2a] J. Khurgin, Appl. Phys. Lett. 21, 2100 (1987); Phys. Rev. B38, 4056 (1988); J. Appl. Phys. 64, 5026 (1988); J. Opt. Soc. Amer. B 6, 1673 (1989); S. Li and J. Khurgin, Appl. Phys. Lett. 62, 1727 (1993).

[3a] R. Normandin *et al*, Electr. Lett. 26, 2088 (1990); D. Vakhshoori *et al*, Appl. Phys. Lett. 59, 896 (1991); R. Lodenkamper *et al*, Opt. Lett. 18, 1798 (1993); S. Janz *et al*, Opt. Lett. 19, 622 (1994).

[4a] S. E. Harris, Appl. Phys. Lett. 9, 114 (1966).

[5a] W. P. Risk, S. D. Lau, and M. A. McCord, IEEE Photon. Tech. Lett. 6, 406 (1994).

[6a] M. L. Bortz, M. A. Arbore, and M. M. Fejer, Opt. Lett. 20, 49 (1995); L. E. Myers, R. C. Eckardt, M. M. Fejer, R. L. Byer, and W. R. Bosenberg, CLEO'95, Paper CThC3.

[7a] J. D. Bierlein and H. Vanherzeele, J. Opt. Soc. Amer. B6, 622 (1989).

[8a] R. DeSalvo *et al*., Opt. Lett. 17, 28 (1992); G. I. Stegeman *et al*., Opt. Lett. 18, 13 (1993).